DESIGN OF AN UNDERGRADUATE 3-AXIS SPACE SCIENCE SATELLITE

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ABSTRACT

The fundamental objectives of the capstone design project in the Department of Astronautics at the United States Air Force Academy are for cadets to learn important engineering lessons by executing a real space mission on a Department of Defense-funded satellite project. FalconSAT-5 is a 153 kg, three-axis stabilized spacecraft being designed and built by cadets and scheduled for launch in December 2009 on a Minotaur-IV from Kodiak, Alaska. The satellite has a space science mission to measure the local state of the ionosphere at ambient conditions with the intelligent Miniaturized Electrostatic Analyzer (iMESA) instrument and higher energy ions with the Wafer Integrated Spectrometers (WISPERS) instrument. There is also an RF receiver that can tune in the VHF and UHF bands in order to measure RF scintillation and correlate large scale ionospheric variations with the local iMESA and WISPERS measurements. One additional science objective is to understand and measure the interaction of generated plasmas with the body of a satellite and the local magnetic fields.

1 INTRODUCTION

It is important that undergraduate engineering students fully understand the nature of the satellite design process as primary program requirements evolve while schedule and cost remain fixed. The history of FalconSAT-5 is an object lesson in how difficult it can be to maintain control of the design process while trying to satisfy stake holders and competing objectives. FalconSAT-5 was created from the conceptual design of a previous proposed effort (FalconSAT-4) that was itself the follow-on to the recently launched FalconSAT-3 spacecraft. FalconSAT-5 started as a three-payload, 30 Watt ion source, gravity gradient stabilized satellite with two plasma instruments and has evolved into an eight-payload, 400 Watt ion source with three reaction wheels.

The formal design and analysis processes implemented by the cadets have allowed them to respond to dynamic requirements changes from the customer while surviving fixed cost and schedule constraints. The fact that there is one hundred percent turnover of the project every May as one class graduates and their "replacements" start their two semesters of work the following August makes documentation and formal engineering processes absolutely critical to the success of the program.

This paper describes in detail the requirements evolution, evaluation of alternatives, trade-off studies, science objectives, engineering processes, and engineering design of this satellite as it prepares for the upcoming launch - and how such aggressive goals can be accomplished in an undergraduate program.

2 DEPARTMENT OBJECTIVES AND HISTORY

The fundamental objectives of the Department of Astronautics (DFAS) at the United States Air Force Academy (USAFA) are to educate and train future officers in the Air Force in satellite and launch vehicle design, analyses, mission planning, acquisition, assembly, integration, testing, and on-orbit operations. These goals are accomplished with a combination of rigorous courses in astronautics and a capstone design experience that involves either a small satellite or a sounding rocket. Supplementing the academic instruction with an opportunity to "learn space by doing space" provides for a unique educational experience.

2.1. FalconSAT History

Beginning in academic year 1995-1996, the Space Systems Research Center (SSRC) – part of the Astronautics Department – introduced the FalconSAT small satellite program. This DFAS, two-semester capstone design course provides a realistic design experience for senior cadets majoring in Astronautical Engineering, Systems Engineering, Physics, Electrical Engineering, Mechanical Engineering, Systems Engineering Management, and other disciplines. The working plan every year is for a cadet team, mentored by a multi-disciplinary group of faculty members, to apply systems engineering processes to design, build, test, and fly a small satellite performing real Department of Defense (DoD) missions. Making the cadet team responsible to a real customer is one of the more critical educational aspects of this program.

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15. SUBJECT TERMS

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The goal for the program is to provide a "hands-on" educational experience for cadets, while applying a high level of practical engineering to solve real-world problems. Based on budgetary, launch vehicle availability, and academic schedule constraints, the program emphasizes developing a basic capability to fly small Air Force and DoD scientific and engineering payloads on three-year cycles.

Also at USAFA is the Space Physics and Atmospheric Research Center (SPARC) in the Department of Physics and the intent is for SPARC to provide the payloads and science motivation for the designated missions. The model for funding the satellite activities uses the functions and responsibilities of the Space Experiments Review Board (SERB) and the Space Test Program (STP). Scientific payloads are briefed by the cadets to the SERB and the DoD organization ranks the presented experiments in terms of scientific and technological importance. STP is tasked with finding launch opportunities for ranked science payloads and that relationship worked successfully for FalconSAT-1, -2, and -3. The core area of expertise in SPARC is plasma instrumentation developed and used to measure ionospheric phenomenology specifically with importance to understanding space weather.

One key "cultural" aspect of the smallsat program at USAFA is to introduce the students to the concept of directed long-range technology development and the need to keep building the knowledge and technology base within a program office. This means that each succeeding spacecraft should build on the lessons learned and capabilities demonstrated by the previous satellites and the corresponding increase in capabilities of the scientific payloads may increase the sophistication of the requirements on the satellite. The bounding constraints to this process are the needs to increase the "cadet content" in all aspects of design, analysis, testing, and operations; the budgetary limitations; and, the need to meet launch vehicle opportunity schedules. These are, of course, all of the very hard problems that are faced every day in the aerospace industry and the reason this course exists.

2.2. FalconSAT-3 and Lessons Learned

FalconSAT-3 was a 50 kg, ESPA compliant, three-axis stabilized, gravity gradient boom, spacecraft with three science payloads and two technology demonstration payloads. Details of that program are described in a companion paper in this proceeding.

One of the important lessons learned had to do with the growth of program requirements after many of the hardware selections had been made. The result was that the processor onboard FalconSAT-3 was not able to meet all of the computing demands of the payloads, the ADCS, and the communication systems. Another lesson learned was the inherent technical, cost, and schedule risks associated flying technologies that have not yet been demonstrated in space. Fifty years after Sputnik space is still hard and vendors and researchers developing their first products for space applications often re-learn many things that only come with experience. For the students understanding this part of acquisition in a research and development environment will pay off huge dividends in the future when they are responsible for large space programs.

2.3. FalconSAT-4

Two payloads from SPARC had been developed that were each a follow-on to the plasma instruments on FalconSAT-3. The first instrument is iMESA (integrated Miniature Electrostatic Analyzer) and this instrument represents significant technology advances over the MESA version developed for FalconSAT-2. The instrument measures ambient plasma temperature and density and can also determine spacecraft charging. The instrument fits on the skin of a spacecraft and successful demonstration on orbit will lead to "peel and stick" versions that can be placed on all DOD low earth orbit (LEO) satellites to enable a much greater number of in situ measurements of the state of the ionosphere. The new version of this instrument uses a proven electrostatic bandpass energy filter for LEO ions and electrons in a new laminate design. The interface to the spacecraft is a simple 4-wire, RS-422 interface and iMESA includes up to 1 GB of memory storage so that the instrument can operate and store data asynchronously from other satellite operations, thereby reducing the satellite processor payload.

The second plasma instrument is known as WISPERS (wafer integrated spectrometers) and is designed to measure and detect the presence of ions in perturbed background plasma. The presence of a cold gas thrusters or ion thrusters in the vicinity of a spacecraft will leave a signature of higher energy, and possibly different species, ions that can be detected by differentiating the energy and density measurements in WISPERS. This instrument is a follow-onto the FLAPS instrument flown on FalconSAT-3 and uses improved micromechanical systems (MEMS) detectors and upgraded electronics. The interface is as simple as iMESA.

	Objective	Threshold
Control	< +/-1.25 all axes	< +/-2.5 all axes
Knowledge	< +/-0.5 all axes	< +/-1 all axes

Table 1. WISPERS and iMESA ADCS Requirements

Both of these plasma instruments impose straightforward ADCS requirements on the satellite and each draws less than 2 watts of power when operating.

Based on this primary set of requirements for two ranked SERB payloads the conceptual design of FalconSAT-4 was completed. The WISPERS payload needed an on-board source of either electric thruster ions or cold gas thrusters ions and a simple source was desired. FalconSAT-3 had flown on the first ESPA (EELV Secondary Payload Adaptor) mission on STP-1 and it was decided that complying with the ESPA Users Guide [1] was the best way to qualify for as many launch vehicle opportunities as possible. The successful aspects of the FalconSAT-3 spacecraft design were used, along with the ESPA constraints, and a gravity gradient boom stabilized satellite was designed.

Mass	181 kg
Volume	60.96 x 71.12 x 96.52 cm
Centre of gravity	50.8 cm from mounting
Fundamental frequency	> 35 Hz

Table 2. ESPA Requirements

On FalconSAT-3 the gravity gradient boom housing extended below the base plate of the spacecraft and extended inside the ESPA ring. This caused no integration issues on STP-1.

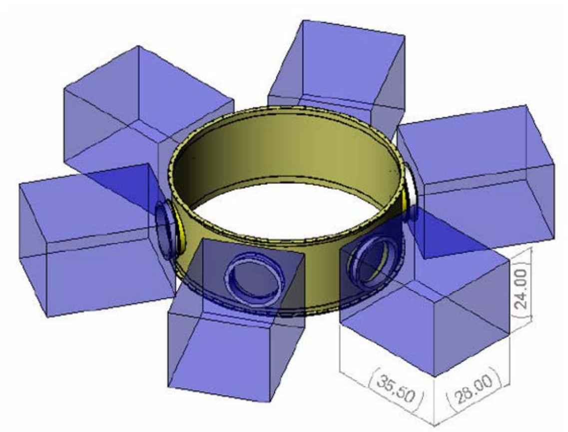

Figure 1. ESPA Volume Constraints

The design that was developed had a mass of less than 100 kg and significant reserve margin for power. It was decided to put a second WISPERS on the end of an 8 meter deployable gravity gradient boom so that small spatial scale changes in the plasma background could be measured as part of the mission.

The design team went through an extensive trade-off study of cold gas thrusters and determined that a nitrogen system with reheat would minimize the cost and risk and provide the ion densities necessary to prove the scientific objectives of the mission. The cold gas thruster system provided a minimum of 150 m/sec delta V to the satellite and the CONOPS were expanded to allow various orbit maneuver experiments to be done in conjunction with the plasma measurements.

There were several ADCS issues identified particularly with respect to maintaining stability during a long, low thrust operation of the nitrogen system. A set of four modulating valves was designed to operate on one face of the spacecraft and maintain orientation in two axes relative to the satellite center of gravity, and account for differential drag torques.

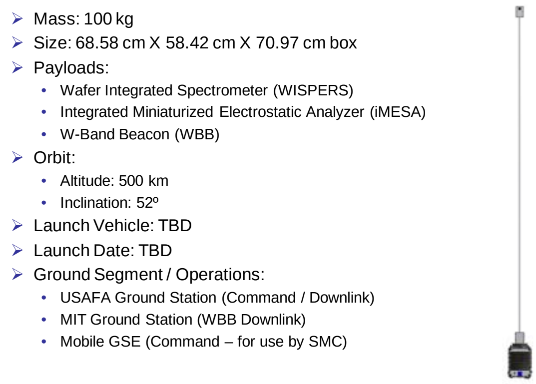

Figure 2. FalconSAT-4 Design and Mission

The design progressed and a complete preliminary design review was held in December 2006. The design was well received but the potential funding agency, STP, did not have the budget to proceed and the students learned another very valuable lesson. A good design by itself, with a recognized mission, does not guarantee funding.

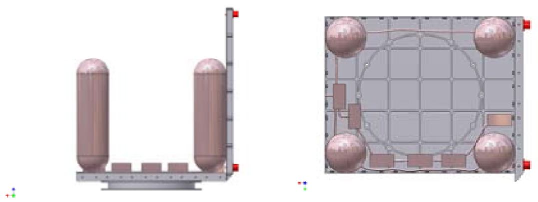

Figure 3. FalconSAT-4 Cold gas Thruster Layout

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3 FalconSAT-5 ORIGINS

The failure to get funding for FalconSAT-4 caused the program to identify other funding sources that had synergistic interests in space science and technology experiments. There has long been an interest in developing ion and cold gas thruster technologies and studying the science of spacecraft-generated plasma interacting with the ambient plasma environment and local magnetic fields. The requirements for FalconSAT-4 were modified to incorporate the full ESPA volume available and the gravity gradient boom retaining structure was pulled inside the satellite to ensure there were no protuberances from the ESPA envelope and nothing that would impact launch vehicle integration.

One additional payload was added to simultaneously measure large scale disturbances of the ionosphere that might be correlated with localized plasma disturbance measurements made by WISPERS and iMESA. The Radio frequency Uplink Signal Strength (RUSS) measurements instrument will measure the scintillation of a signal from ground sources in the UHF and VHF bands. The amplitude variations in the received signal strength will be used to perform a tomographic re-construction of variations in the ionosphere in two dimensions.

3.1. Preliminary Design Review

One of the smallsat program goals for FalconSAT-5 was to build a structure that would be ESPA compliant and become a standard bus that could be easily replicated and constructed at USAFA with existing milling machines. An aluminium isogrid structure constructed of six panels was selected. The panel connecting bolts and nuts are all externally accessible so that assembly, and disassembly, are straightforward. The isogrid structure also allows placement of avionics components throughout the structure, mounted on any panel, or in a central stack.

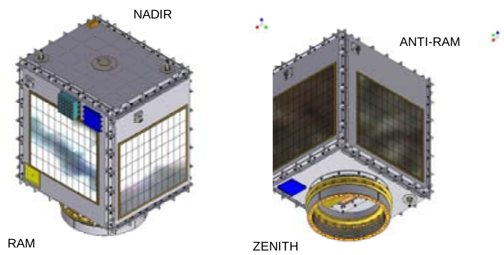


Figure 4. FalconSAT-5 PDR External Views

Using body-mounted solar panels and extending the dimensions of the panels as large as possible enables a power system with a nominal 60 – 75 OAP (on-orbit average power) performance level.

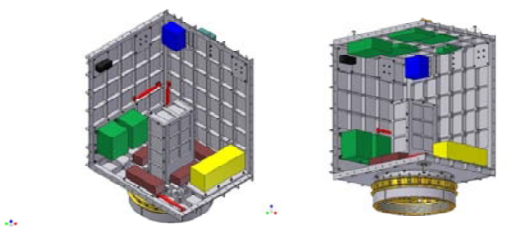


Figure 5. FalconSAT-5 PDR Internal Views

The base plate was designed to use the 15 in (38.1 cm), 24-bolt motorized lightband, which has now become a standard requirement for STP launches. Pulling the gravity gradient boom inside the structure did have a minimal impact since the structural design allows for avionics distributed on the side panels. One additional benefit is simple control of the center of gravity.

	Mass Budgeted (kg)	Design Mass (kg)	Margin (kg)
Payload	10.66	9.80	0.86
Structure	34.01	31.95	2.06
Power	8.05	7.52	0.53
CDH	5.62	5.33	0.29
ADCS	9.04	8.47	0.58
Comm	2.60	2.20	0.40
Total Bus	70.00	65.27	8.73
Interface	10.00	9.77	0.23
Total with Interface	80.00	75.03	4.96

Table 3. FalconSAT-5 PDR Mass Budget

The presumed ion source at this time was thought to be approximately 30 W peak power and 5 kg mass and was easily accommodated inside the structure.

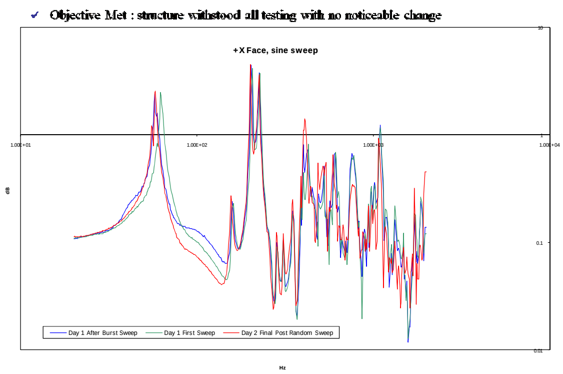


Figure 6. FalconSAT-5 Sine Sweep Results

A structural engineering model (SEM) was built by the cadets and taken to Kirtland Air Force Base (KAFB) for vibration and shock testing. The fundamental frequency was above 60 Hz and there was minimal shift in that after two days of extensive testing. This validated the approach to the structural design. The Class of 2007 graduated and passed the design onto the incoming class.

3.2. Change In Requirements

Before the next class arrived there were significant changes in the requirements. Two items particularly affected the design and schedule for the satellite. The first change was the removal of the gravity gradient boom to allow for better fidelity in modelling the plasma interactions with the spacecraft. That resulted in reaction wheels being added for the ADCS system.

The second major change was in the size, mass, and power requirements for ion source. Since this was an opportunity to get flight heritage on a new thruster

system, and better understand plasma interactions over a range of power levels, the ion source payload became an ion and cold gas source for use by WISPERS to meet the SERB objectives for the mission. A delta-PDR design review was conducted in preparation for the final design effort.

4 Final FalconSAT-5 Design

FalconSAT-5 was one of four satellites manifested on an STP launch of a Minotaur-IV provided by Orbital Sciences Corporation (OSC). The target launch date was set as 1 Dec 2009 and the launch site will be the Kodiak Launch Complex (KLC) on Kodiak Island, Alaska.

4.1. Mission Objectives and CONOPS

The evolving requirements on FalconSAT-5 forced the design team to weed out those aspects of the design that were no longer essential to meeting the objectives of the mission. The focus of the mission became the need to make correlated plasma and RF measurements so that both the understanding of space weather and the detection of anomalous ionospheric events became the sole rationale for the mission.

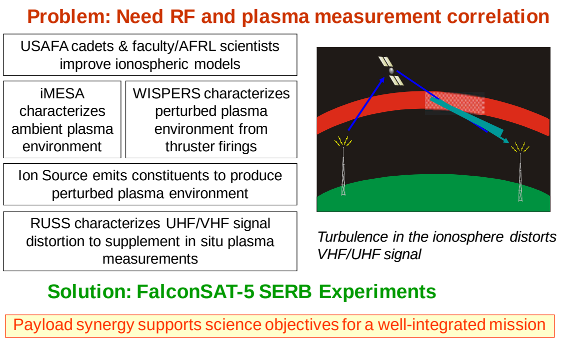


Figure 7. FalconSAT-5 Science Objectives

The iMESA instrument will be able measure ion density and temperature and determine spacecraft charging levels. This determination of inhomogeneous structures in the ionosphere helps identify such phenomena as plasma bubbles, which are capable of interfering with GPS and communications signals. WISPERS will measure perturbations of the ambient plasma at slightly higher energy levels. In order to understand the relationship between the local plasma measurements of WISPERS and iMESA and possible large-scale structures in the ionosphere the RUSS payload will simultaneously measure the amplitude variations of terrestrial RF signals.

The nominal orbit chosen by STP for this mission is a 650 km circular orbit at an inclination of 72^0. This gives excellent coverage of the ground station at USAFA and enables the plasma instruments to take their measurements at high latitudes where they can sample as many magnetic field strengths and plasma densities as possible.

Calculations of the expected orbital lifetime of the satellite were done using various assumptions about high and low drag cases, tumbling and non-tumbling orientations, different altitudes, and different mass assumptions. This is always an educationally instructive exercise to perform in order to understand how sensitive many aerospace calculations are to small changes in the initial conditions.

Orbital Parameters	Lifetime (years)	Lifetime (orbits)
650 km, 120 kg, min Cd	62.8	344321
650 km, 120 kg, max Cd	40.8	223445
650 km, 92 kg, max Cd	30.1	164864
650 km, 92 kg, min Cd	44.9	245397
600 km, 120 kg, min Cd	31.2	172083
600 km, 120 kg, max Cd	19.2	105737
600 km, 92 kg, min Cd	23.8	131881
600 km, 92 kg, max Cd	17.2	95159

Table 4. FalconSAT-5 Expected Orbital Lifetime

The concept of operations for the satellite revolves around taking as much science data as possible while balancing the restrictions of a single ground station

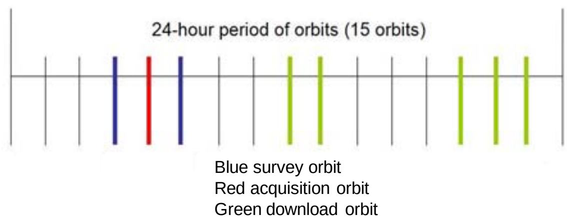
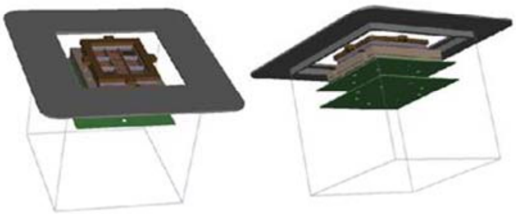


Figure 8. FalconSAT-5 Sequence of Operations

The result is that the satellite will alternately take WISPERS and iMESA data in both survey and acquisition modes and then store the data onboard until the next opportunity to download data. It is expected that about three orbits every 24 hours can be devoted to collecting raw data that will be downlinked over five orbits. As more is learned about the plasma measurements various lossless and lossy data compression algorithms will be uploaded to the satellite in order to perform on orbit compression and science extractions

4.2. Payloads and Requirements

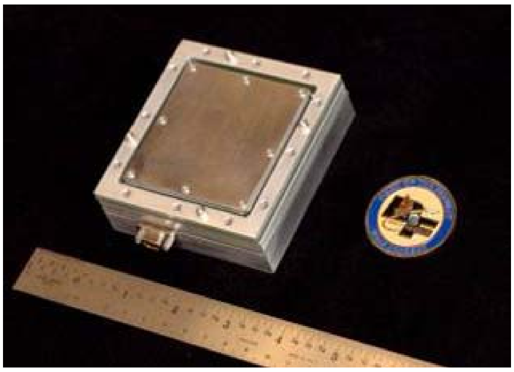
The WISPERS requirements had been well developed during the FalconSAT-4 design phase and the ADCS and data flow requirements remained essentially unchanged. The RS-422 serial port will communicate at 115 kbps and the instrument can store up to 1 GB of data in its own COTS memory. A similar design for iMESA allows the spacecraft processor to distribute data storage and manage data flow without having to resort to a large, separate solid-state date recorder (SSDR). The power, mass, and cost of equivalent SSDRs was beyond the budget of the project.



Schematic of WISPERS showing close-up of 7 detectors, and showing entire assembly

Figure 9. WISPERS Instrument

iMESA precursors have been delivered to the International Space Station (ISS) and that experience has been very useful in developing the FalconSAT-5 version of the instrument.



iMESA precursor—Smart MESA integrated on MISSE-6

Figure 10. iMESA Payload

The table below summarizes the ADCS and data storage and handling requirements for FalconSAT-5. The attitude knowledge and control requirements are at a performance level that may be accommodated by relatively simple COTS sensors.

Altitude	650 km	
Inclination	72°	
	Threshold	**Objective**
Attitude Knowledge (all directions)	± 1° (3σ) knowledge (WISPERS) ±1° (3σ) knowledge (iMESA) 1 observation/ sec	±0.5° (3σ) knowledge (WISPERS) ±0.5° (3σ) knowledge (iMESA) 10 observations/sec
Attitude Control (all directions)	±2.5° (3σ) (WISPERS) ±4° (3σ) (iMESA)	±1.25° (3σ) (WISPERS) ±2° (3σ) (iMESA)
Data Rate (acquisition mode)	1.3 Mb storage/orbit (iMESA) 4.9 Mb storage/orbit (WISPERS)	12.6 Mb storage/orbit (iMESA) 49.4 Mb storage/orbit (WISPERS)
Slew Rate	90° in 10 minutes (RUSS)	90° in 10 minutes (RUSS)

Table 5. FalconSAT-5 Summary ADCS and Data Requirements

The following two figures show internal and external views of the final satellite design. The use of the six aluminum isogrid panels allows a mix of distributed avionics and stacked avionics trays within the same structure. The motorized lightband mounts to the base plate of the structure with an adaptor ring. The other half of the lightband will mount to the payload adaptor plate on the launch vehicle.

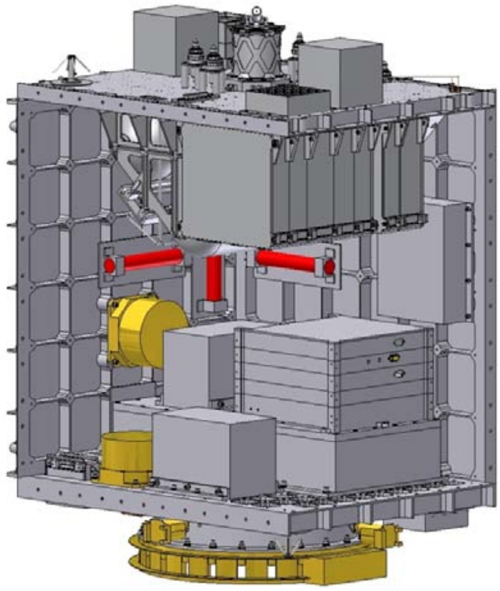


Figure 11. FalconSAT-5 CDR Internal View

As can be seen in the exterior view almost all of the available surface area on the four side panels is covered with body mounted solar cells. The RUSS antennas are shown in their fully deployed position.

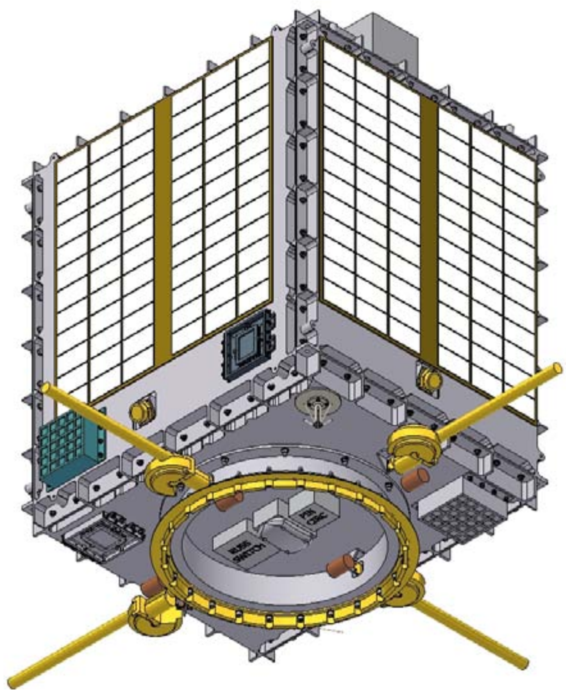


Figure 12. FalconSAT-5 CDR External View

The primary load on the structure occurs at the mounting ring on the base plate. The isogrid pattern is machined into the base plate in such a way as to keep stress concentrations from exceeding design limits for the material.

4.3. Thermal Analyses

FalconSAT-5 is designed to orient in any direction and will experience periods of peak power draw in both sunlight and eclipse conditions. Distributing the avionics on the sides of the panels, and stacking some of the avionics trays on top of the battery box, requires that detailed thermal analyses be performed to fully understand the range of environments inside and outside the spacecraft. This is another sophisticated engineering analysis that can be performed by a senior-level undergraduate student with the right tools and the right approach to the problem.

SINDA is the thermal analysis tool used in the smallsat program and the cadets start with a solid model generated in Inventor. The exported file is imported to SINDA and all of the material properties, thermal interfaces, and component heat loads are identified. Several different orbits, sun conditions, satellite orientations, and operating scenarios are evaluated to determine worst case thermal conditions.

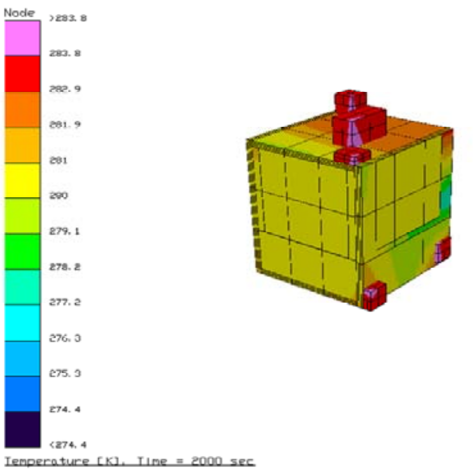


Figure 13. Example FalconSAT-5 Thermal Analysis Results

The analysis to date has not found any serious problems and the specification for all components has remained at 0 – 30C for operating ranges and -20 – 50C for survival ranges. The bare aluminium will be coated with an alodyne finish to prevent surface oxidizing and help with passive thermal control.

4.4. Electric Power System

The electric power system (EPS) consists of four body mounted solar panels, two battery charge regulators (BCR), and a single battery box consisting of 66 'D' cell Sanyo NiCad batteries. The solar cells are 26% efficient triple junction GaAs and are configured as four strings per panel. Two strings from each panel feed each BCR so that a failure of one BCR will not cause mission failure.

There has been some recent concern about the Sanyo D cell NiCad batteries since manufacturing was changed from Japan to China and there were some changes made in the internal spacer ring. To understand the risk the cadets tested several of the batteries to 18 grms random vibration levels and saw no failures. The prototype battery box for FalconSAT-5 has been separately qualified to ESPA vibration requirements with no apparent loss of functionality.

The nominal average power load on FalconSAT-5 is between 55 and 75 W as a function of what experimental sequence is being executed. The ion source has the ability to pull a load of 500 W for short periods of time (minutes) and during that time the total power draw on the EPS can be as high as 620 W. The worst case analysis of the EPS results in occasional depth of discharge on the battery of 44%. This happens for less than 1000 cycles during the life of the satellite and the majority of discharge cycles over three years are less than 15%. The EPS software is being designed to deep cycle and erase the memory affect of the NiCad battery on orbit if necessary.

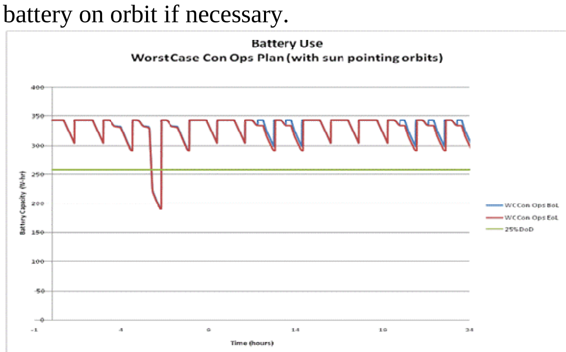


Figure 14. Worst Case Battery Depth of Discharge

The cadets were required to accurately model the orbits over a one year period and find the worst combination of eclipse, mission and experiment profiles, maximum download and transmitter operations and determine if the battery design was expected to last a minimum of three years.

4.5. ADCS

The design of the ADCS system was significantly constrained by budget considerations. The nominal 0.5^0 to 1^0 degree knowledge requirements will be met using a three-axis magnetometer and 0.1^0 digital sun sensors. In the absence of slewing maneuvers the onboard Kalman filtering algorithms are expected to meet these requirements. However, during slewing maneuvers, or

excessive torque disturbances from the ion or cold gas sources, the attitude knowledge capability will be degraded. The reaction wheels being used do not have an organic rate sensor and the addition of MEMs rate sensors is being evaluated in order to provide additional state measurements to the Kalman filter.

Commissioning Phase	
De-tumble phase	Attitude/rate acquisition
	Detumble – torque rods (B-dot controller)
Stabilization, 3-axis control	Initial dampening of libration motion
	Torque rods and wheel(s)
Normal Operations	
3-Axis stabilization mode	Point in arbitrary direction
Downlink mode	Random/nadir pointing
Slew maneuver	Pointed at ground station during pass (90 deg / 10 min)
Safe hold	Torque rods only
Thermal control mode	Slew about yaw axis
Momentum dumping	Use torque rods to dump stored reaction wheel momentum

Table 6. FalconSAT-5 ADCS Modes

Tab. 6 shows the various control modes on FalconSAT-5. Torque rods will provide the control authority to de-tumble the satellite following separation and torque rods and reaction wheels will be used for the initial three-axis stabilization. The torque rods will also be used to provide momentum dumping for the reaction wheels.

Several variations of Kalman filter have been developed and analyzed as part of the design process and detailed simulations have determined the largest possible torque disturbances from the ion or cold gas sources that can be accommodated while still meeting control requirements.

4.6. Avionics Design

The design of the avionics is based on intelligent power and data nodes (IPDR) provided by Microsatellite Systems, Inc. (MSI) in Littleton, Colorado. These nodes consist of a radiation-hard, FPGA implementation of a 32-bit SPARC architecture; another FPGA for hardware interfaces; multiple serial and spacewire ports; and, a power management capability that incorporates several 28 V switches. The processors are each rated at 4 MFLOPs and each processor has 128 MB of available data storage. There is 2 MB of program storage space on each processor. Each node will consume approximately 8 W.

One processor is designated as the command and data handling processor (C&DH) and it will handle all of the communication, ADCS, and EPS functions. The second processor will handle all of the payload functions. That includes serial port connections to WISPERS, iMESA, RUSS, ion source and a GPS receiver. The GPS receiver primary function is to provide accurate timing for all of the experiments so that the resulting data can be carefully correlated. The 1 pps signal from the GPS receiver will be distributed to the IPDR node and to the payloads that need that accurate a timing signal.

4.7. Communication, Data Flow, and Link Margins

The 650 km by 72^0 orbit provides very good access to the USAFA ground station at 39^0 latitude. Over the course of one year there is an average of 66 minutes of contact per twenty four hours. The communication system will consist of a UHF uplink at 9.6 kbps using GMSK modulation and an S-band downlink at 115 kbps that also uses GMSK modulation.

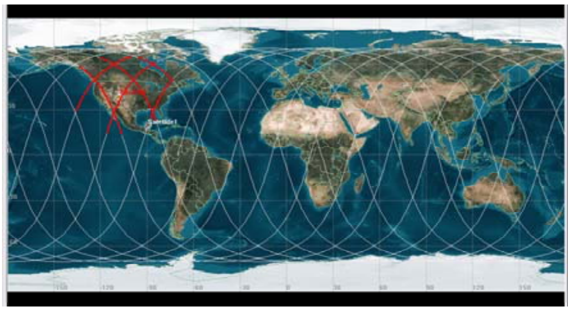


Figure 15. FalconSAT-5 Ground Station Coverage

Data flow management on FalconSAT-5 will be a complicated task for the future operators. The WISPERS and iMESA instruments have the ability to generate enormous quantities of data. A reasonable experimental plan has been developed that meets all of the SERB objectives in one year and that uses the distributed data storage architecture among the various payloads and the IPDR. The IPDR will be able to execute compression algorithms that are developed during the course of the flight experiment.

	Component	**Data Collected (1)**
Objective Acquisitions	iMESA & WISPERS	**62.2 MB/orbit**
	RUSS & SSASM	**2.10 MB/orbit**
Total Objective		**64.3 MB/24 hours**
Threshold Survey	iMESA & WISPERS	**0.90 MB/orbit**
	RUSS & SSASM	**0.90 MB/orbit**
Total Threshold (2)		**3.6 MB/24 hours**
Telemetry & SOH		**1.28 MB/24 hours**
TOTAL DATA COLLECTION		**69.2 MB/ Acquisitions Sequence**

Table 7. FalconSAT-5 Data Flow

Tab. 7 shows the typical accumulation of data during normal operations.

4.8. Software

At the undergraduate level the development and testing of proven flight software is perhaps the largest technical challenge on the program. The students have good analytical skills and have significant experience in using MATLAB and Simulink to model physical systems and design controllers. However experience in writing code for embedded controllers, communication systems, and general satellite housekeeping tasks is non-existent and teaching that as part of the capstone design course has become a high priority.

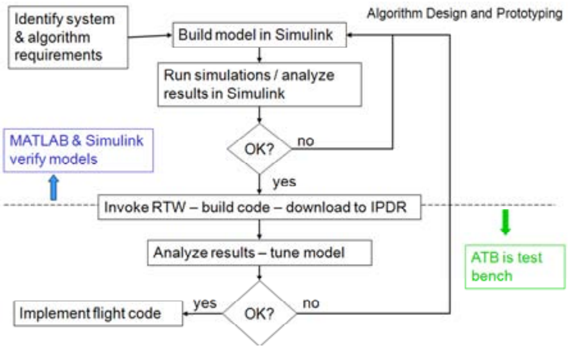


Figure 16. FalconSAT-5 Software Development

Fig. 16 shows an outline of the development process that will be attempted for parts of the flight code. The analyses that are done in Simulink will be used to test and validate algorithms. The Real-Time Workshop capability will be used to generate flight code for the IPDR and that code will be downloaded to the processors and tested. The real-time operating system (RTOS) for the IPDRs is VxWorks from Wind River. In the event that this process is not successful then the Simulink validation will lead to writing pseudo-code for all of the tasks to be executed on orbit. The pseudo code then will be translated into C and the tasks for the IPDRs will be built in the Wind River development environment.

4.9. Configuration Control

Fig. 17 shows the mass growth in the satellite from the very beginning of the conceptual design through the final critical design and subsequent testing ands analysis. This scale of mass growth is not unusual in research and development programs and successive classes of students have had to learn when to keep the customer happy and when to say no. Great emphasis is placed upon documentation since not only have the requirements changed dramatically but there is 100 percent turnover in the student work force every year. The learning focus of this exercise is to know the difference between freezing a design too early in the process and managing change efficiently.

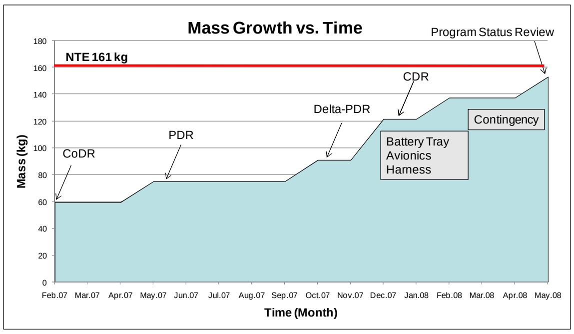


Figure 17. FalconSAT-5 Mass Growth

Tab. 8 shows the final mass budget for the satellite. There are still some sizable contingencies and mass margins carried at this stage of the project.

Subsystem	**Mass (kg)**
Avionics Stack	6.5
ADCS	8.7
CDHS	6.6
Comm	6.9
EPS	25.9
Payloads	35.9
Structure	52.9
Total (CBE)	138.4
Contingency	15.0
Total (CBE + Contingency)	153.4
Margin (5%)	7.3
Total (including margin)	**160.7**

Table 8. FalconSAT-5 Final Mass Budget

4.10. SEM2 Testing

In April of 2008 a second structural engineering model (SEM2) was fabricated and assembled by the cadets since the mass had changed so much from the previous year. SEM2 was also taken to KAFB and subjected to ESPA qualification loads. The testing was accomplished with the flight motorized lightband and the worst case axis had a fundamental frequency (rocking mode of the base plate) of 40 Hz, which is well above the 35 Hz ESPA minimum. The same test was repeated without the lightband to determine the effect of the lightband and the fundamental frequency of just the structure was found to be 54 Hz. In all cases the SEM2 passed the tests and saw minimal shifts in fundamental frequency and no significant reduction in torque values in the assembly bolts.

5 SUMMARY AND CONCLUSIONS

FalconSAT-5 is an example of how difficult it can be to balance the competing requirements among real programs and student education needs and academic schedule constraints. However, by requiring the students to be an integral part of the solution of these problems, they are exposed to all of the vagaries and difficulties of the space business. Space is still hard and engineering is still the *disciplined* art of the possible. Exposing students to this environment while they are undergraduates is essential for the future success of the space industry.

6 REFERENCES

1. *Secondary Payload Planner's Guide For Use On The EELV Secondary Payload Adaptor*, DoD Space Test Program, July 2006.